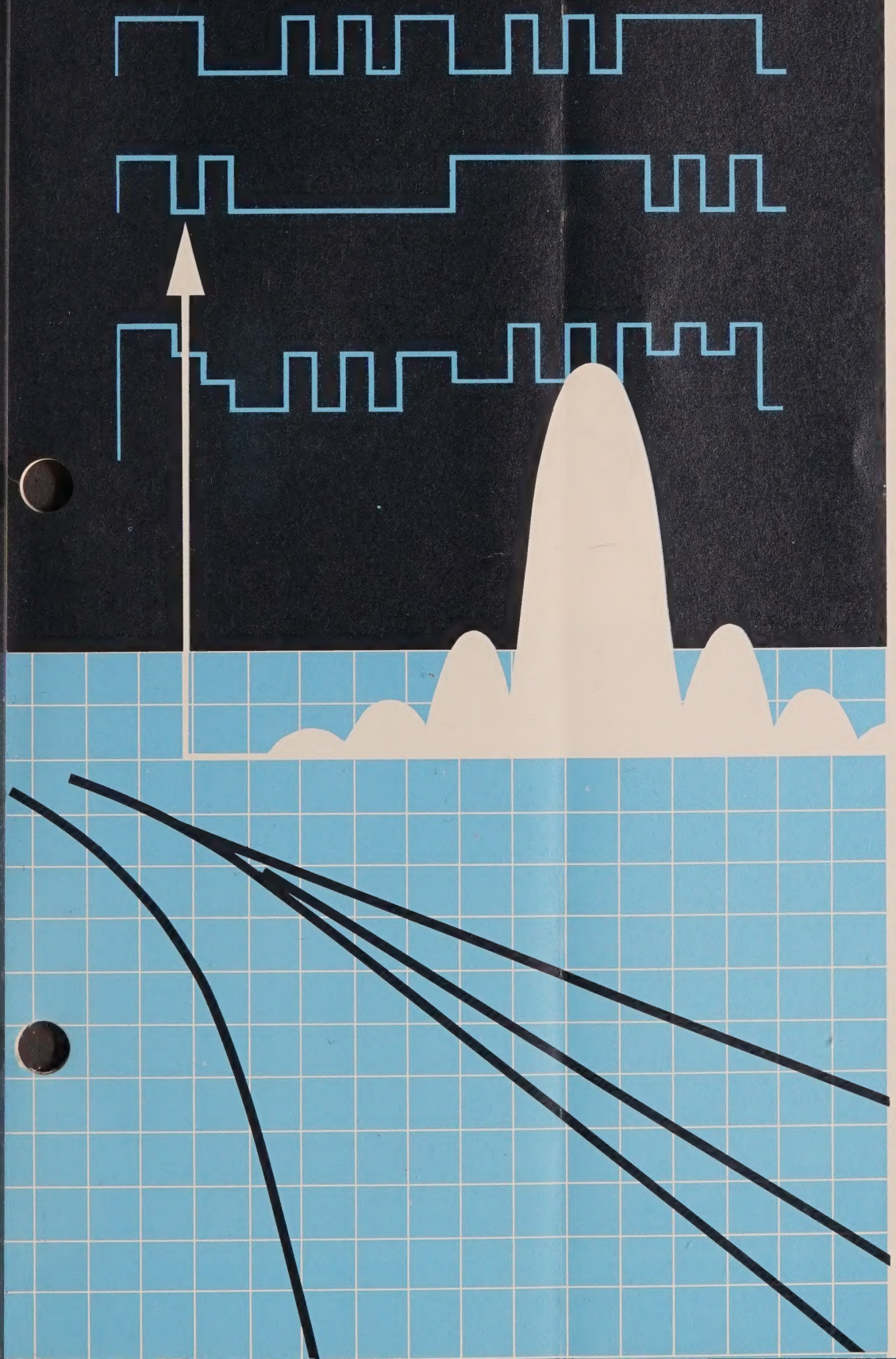
Vol. 7 No. 5 September/October 1980

FSK: Signals and Demodulation



WATKINS-JOHNSON COMPANY
Tech-notes

Frequency shift keying (FSK) is the most common form of digital modulation in the high-frequency radio spectrum, and has important applications in telephone circuits. This article provides a general tutorial on FSK in its many forms. Both modulation and demodulation schemes will be discussed.

Binary FSK

Binary FSK (usually referred to simply as FSK) is a modulation scheme typically used to send digital information between digital equipment such as teleprinters and computers. The data are transmitted by shifting the frequeny of a continuous carrier in a binary manner to one or the other of two discrete frequencies. One frequency is designated as the "mark" frequency and the other as the "space" frequency. The mark and space correspond to binary one and zero, respectively. By convention, mark corresponds to the higher radio frequency. Figure 1 shows the relationship between the data and the transmitted signal.

The most commonly used signal parameters for describing an FSK signal are shown in Figure 2. The minimum duration of a mark or space condition is called the element length. Typical values for element length are between 5 and 22 milliseconds, but element lengths of less than 1 microsecond and greater than 1 second have been used. Bandwidth constraints in telephone channels and signal propagation considerations in HF channels generally require the element length to be greater than 0.5 millisecond. An alternate way of specifying element length is in terms of the keying speed. The keying speed in "bauds" is equal to the inverse of the element length in seconds. For example, an element length of 20 milliseconds (.02 seconds) is equivalent to a 50-baud keying speed.

Frequency measurements of the FSK signal are usually stated in terms of "shift" and center frequency. The shift is the frequency difference between the mark and space frequencies. Shifts are usually in the range of 50 to 1000 Hertz. The nominal center fre-

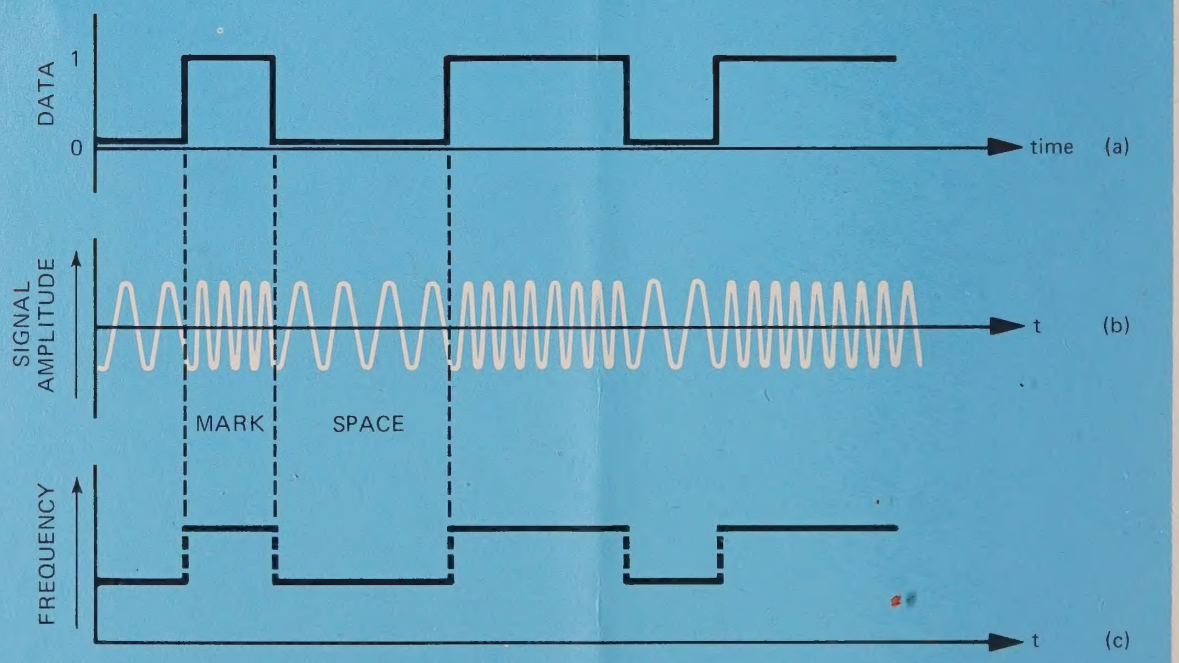


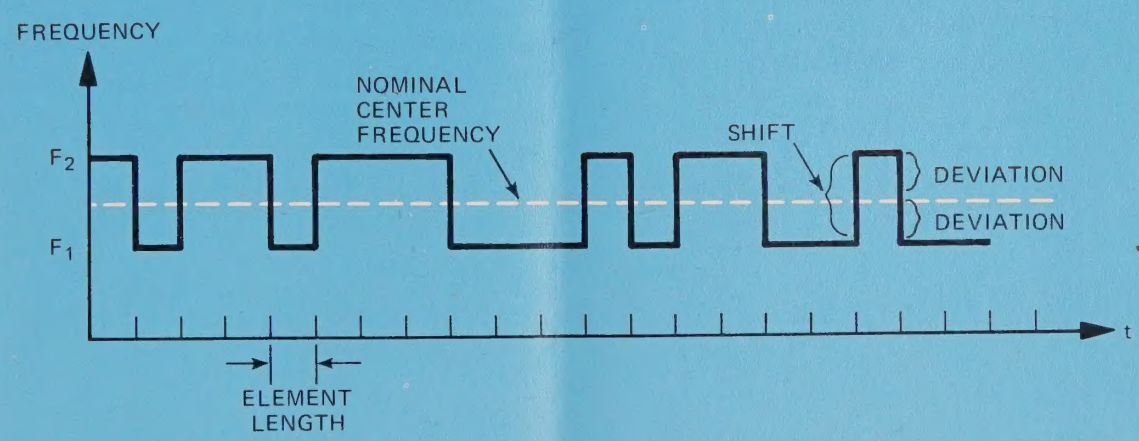
Figure 1. FSK modulation. Binary data (a) frequency modulates the carrier to produce the FSK signal (b) which has the frequency characteristic (c).

quency is halfway between the mark and space frequencies. Occasionally the FM term "deviation" is used. The deviation is equal to the absolute value of the difference between the center frequency and the mark or space frequencies. The deviation is also equal, numerically, to one-half of the shift.

FSK can be transmitted coherently or noncoherently. Coherency implies that the phase of each mark or space tone has a fixed phase relationship with respect to a reference. This is similar to generating an FSK signal by switching between two fixed-frequency oscillators to produce the mark and space frequencies. While this method is sometimes used, the constraint that transitions from mark to space and vice versa must be phase continuous ("glitch" free) requires that the shift and keying rate be interrelated. A synchronous FSK signal which has a shift in Hertz equal to an exact integral multiple (n = 1, 2,...) of the keying rate in bauds, is the most common form of coherent FSK. Coherent FSK is capable of superior error performance but noncoherent FSK is simpler to generate and is used for the majority of FSK transmissions. Noncoherent FSK has no special phase relationship between consecutive elements, and, in general, the phase varies randomly.

Many different coding schemes are used to transmit data with FSK. They can be classified into two major groups: synchronous and asynchronous. Synchronous transmissions have mark-to-space and space-to-mark transitions in synchronism with a reference clock. Asynchronous signals do not require a reference clock but instead rely on special bit patterns to control timing during decoding. Figure 3 compares synchronous and asynchronous keying.

A very common asynchronous coding system is the 5-bit Baudot code with leading start (release) and trailing stop (latch) elements. Originally designed for use with mechanical teleprinters, the system is "latched" until a "release" element is received, causing the printer to interpret the next 5 element intervals as code bits. The binary values of



$$\text{SHIFT} = |F_2 - F_1|$$

$$\text{CTR FREQ} = \frac{F_2 + F_1}{2}$$

$$\text{DEVIATION} = \frac{\text{SHIFT}}{2} = \left|\frac{F_2 - F_1}{2}\right|$$

$$\text{KEYING SPEED IN BAUDS} = \frac{1}{\text{ELEMENT LENGTH (IN SECONDS)}}$$

Figure 2. FSK parameters.

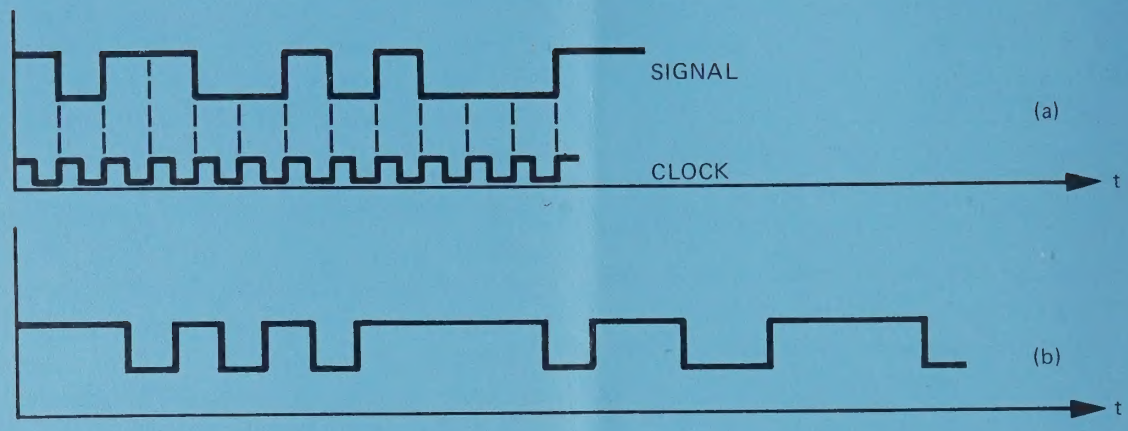


Figure 3. Synchronous (a) and asynchronous (b) signals.

the 5 bits correspond to a particular character. In Figure 4, the two character patterns correspond to the characters "C" and "W" respectively. The 5 "information" bits are immediately followed by a stop or "latch" bit lasting a minimum of 1.42 element lengths. The latch bit stops the printing decoder until the decoder is again started by the next "release" element. The length of the latch bit may be very long between characters, especially in the case of manually generated characters where the operator types more slowly than the system can transmit characters. The noninteger minimum latch element length of 1.42 elements and the random nature of manual character generation emphasizes the asynchronous nature of this scheme.

A common synchronous system uses Moore ARQ coding. The Moore code is a 7-bit-per-character code with no start or stop elements. Bit synchronization is maintained by using a reference clock which tracks the keying speed of the received signal. Character synchronization is maintained by sending periodic "idle" or "dummy" characters between valid data characters.

Frequency Division Multiplex (FDM)

Several FSK signals can be transmitted simultaneously in a given frequency band by assigning different center frequencies to each of the FSK signals. This method of simultaneous transmission is called FDM. In the radio spectrum several audio FSK signals are often combined for transmission by a single-sideband transmitter. This form of FDM is often called Voice Frequency Telegraph (VFT). To minimize

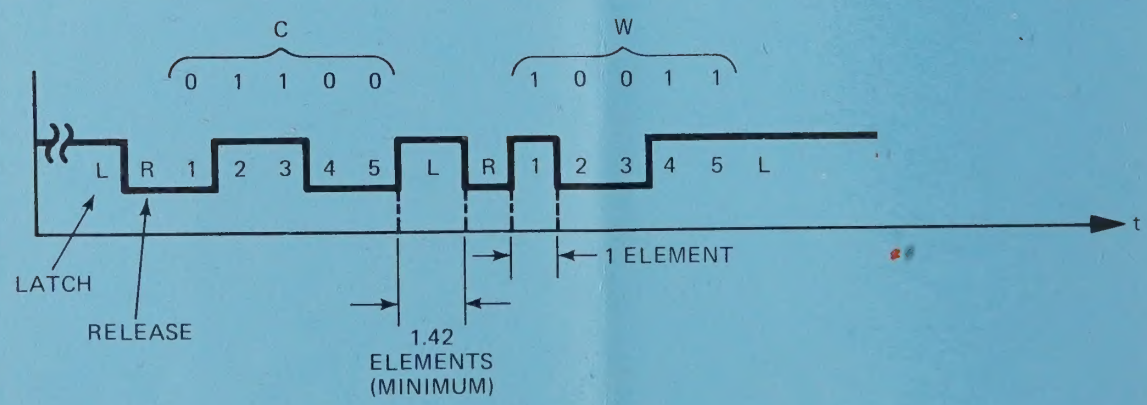


Figure 4. Baudot coded start-stop system (typical).

bandwidth, the individual FSK channels usually have "narrow" shifts of between 50 and 200 Hertz. A typical FDM system is shown in Figure 5. HF radio systems usually transmit 16 tone channels, but 24 or more tone channels per 3-kHz sideband are possible. Telephone standard is typically 12 or 24 tone channels per 3-kHz sideband (voice band).

HF radio is subject to random multipath signal fading. The relatively narrow-band nature of this fading phenomenon causes only one or two tone channels to be severely affected at any moment. As a defense against fading, it is common practice to run duplicate data in tone channels in the same FDM group. If the duplicate channels are separated by 1 kHz or so, the fades in one tone channel are relatively uncorrelated with fades in the duplicate channel. For this reason, it is possible to take advantage of in-band frequency diversity to greatly improve system performance against multipath fading. In a 16-channel HF scheme, channel 1 is paired with channel 9, channel 2 with channel 10, etc. The disadvantage of this scheme is that only half as many channels can be transmitted due to duplication. An alternate approach to the diversity problem is to use "interleaved" FDM.

Interleaved FDM takes advantage of the fact that a mark tone's activity is the complement of the space tone activity. This suggests that reception of the mark or space alone is sufficient to determine the transmitted data. If the mark and space tones are separated by 1 kHz or so, they can be separately detected for frequency diversity. To combine widely separated mark and space tone pairs into a single FDM sideband, each pair must be inter-

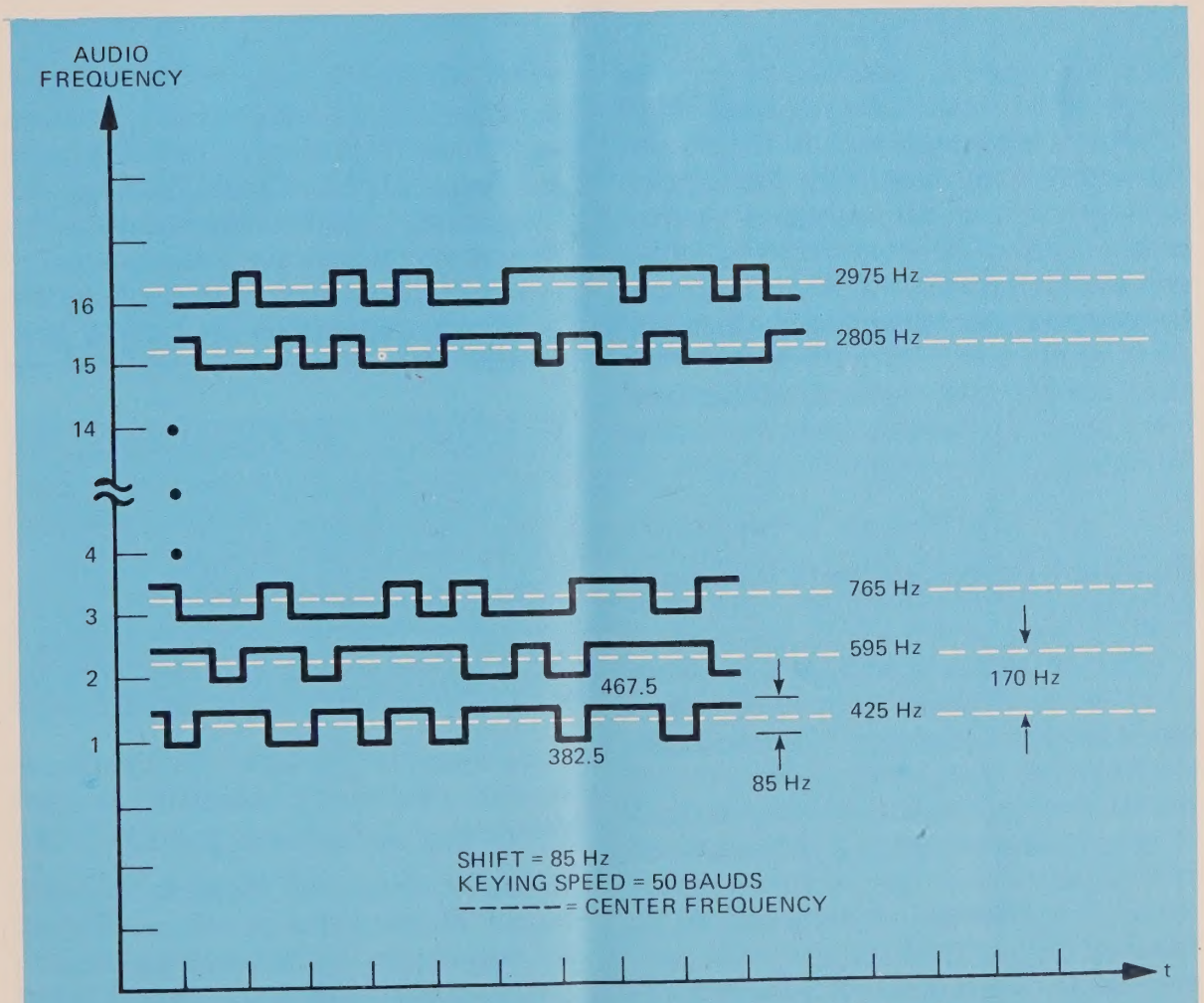


Figure 5. Typical 16-channel FDM (VFT) FSK signal.

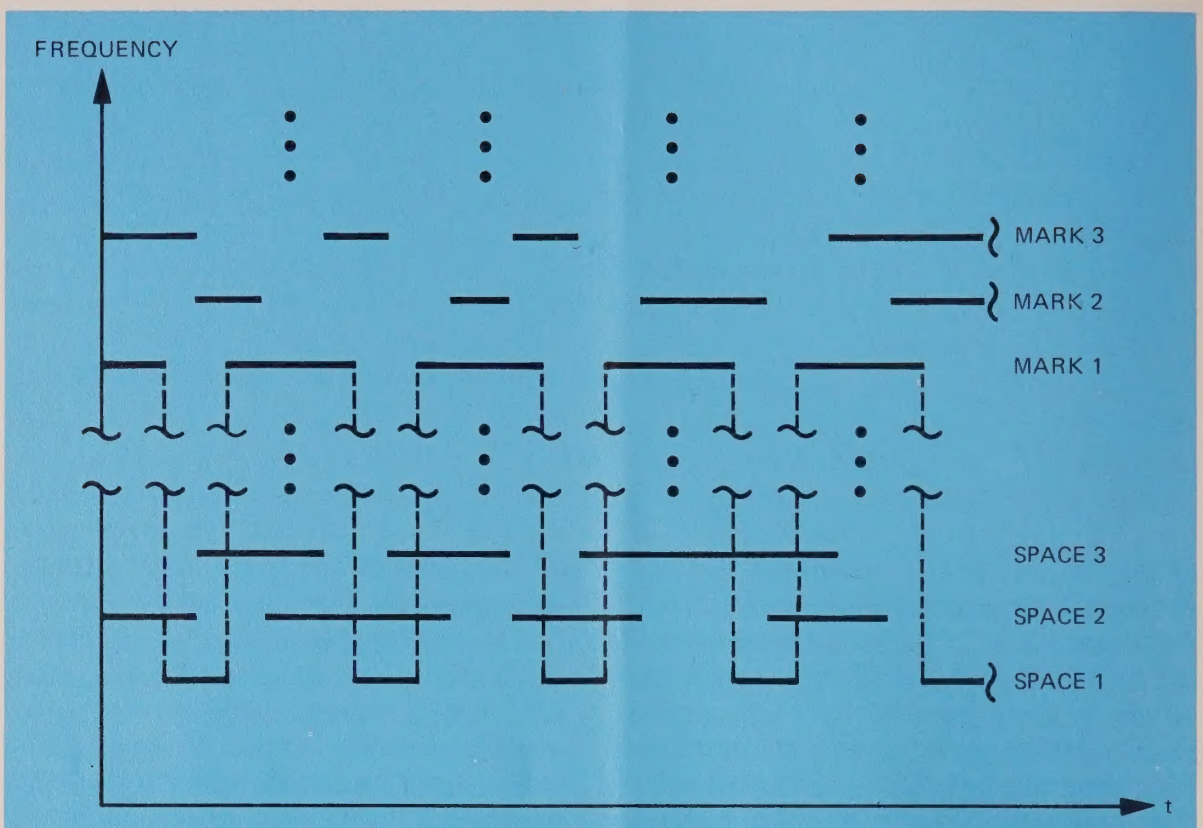


Figure 6. Interleaved FDM FSK signal.

leaved with the other pairs. This scheme is demonstrated in Figure 6. By interleaving the FSK tone pairs it is possible to achieve good performance against multipath fading without sacrificing bandwidth efficiency. In spite of the advantages of interleaving, it is a less popular scheme than simple tone duplication because the required demodulator is more complex.

Double Frequency Shift Keying (DFSK)

DFSK, sometimes called DFS or twinplex, is a scheme to transmit two independent binary data streams by shifting the frequency of a single carrier among four discrete frequencies. Figure 7 shows a code table to convert two binary bits to one of four output states. For example, if bit X and bit Y are 1 and 0, respectively, the output state is C. If each of the four output states (A through D) is assigned to a corresponding FSK frequency, then it is possible to transmit any two bits as a single element. Figure 8 illustrates a typical DFSK signal. Because the two binary channels are independent, they may contain any combination of synchronous and asynchronous signals. It is not uncommon to have a teleprinter in one channel and a Morse code signal in the other. Bit synchronization between channels is not required.

INPUT BITS X	INPUT BITS Y	OUTPUT STATE
0	0	A
0	1	B
1	0	C
1	1	D

Figure 7. One-of-four code table for two binary bits.

In the example of Figures 7 and 8, output states A through D are assigned to frequencies f_1 through f_4, respectively. There are 24 different ways (4 factorial permutations) that the four states can be assigned to four

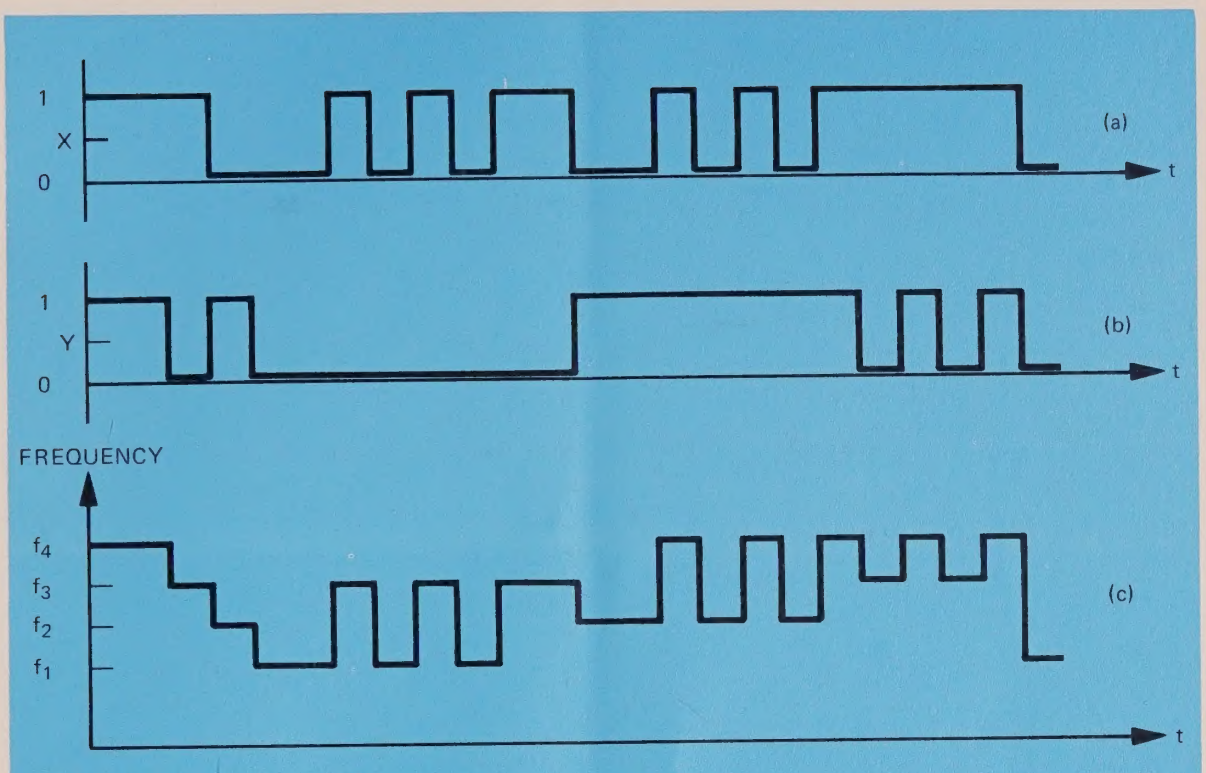


Figure 8. DFSK signal. Digital channels X (a) and Y (b) are combined into a single DFSK signal (c).

frequencies. Because the DFSK signal transmits only one frequency at a time, transmitter power efficiency can be much higher than an FDM transmitter, which has a linearity requirement to prevent intermodulation of tones.

FSK Demodulation

The demodulation methods for FSK can be divided into two major categories: FM detector demodulators and filter-type demodulators. Early designs for FSK demodulation tended to be FM detector types so they will be discussed first.

FM Detector Demodulators

The FM detector demodulator treats the FSK signal as a simple FM signal with binary modulation. Figure 9 shows a functional block diagram for an FM detector-type demodulator. The FSK signal is bandpass-filtered to remove out-of-band interference and then limited to remove AM interference. The limited signal is FM-detected to produce a positive output for a mark condition and a negative output for a space condition. The raw, detected signal is lowpass-filtered to remove noise components at frequencies above the baud rate, and, finally, the decision circuit makes all positive voltages into binary 1's and all negative voltages into binary 0's.

This type of demodulator was very popular due to its relative simplicity and its noncritical tuning. Phase-locked-loop (PLL) demodulators are a more recent technique, but they have very similar performances to that of FM detector demodulators. However, for a small class of signals specifically designed for PLL demodulation, PLL demodulators may perform better than FM detector demodulators. FM detector-type demodulators are somewhat complex for FDM work and cannot generally be used with interleaved FDM signals. They are also not commonly used with DFSK signals.

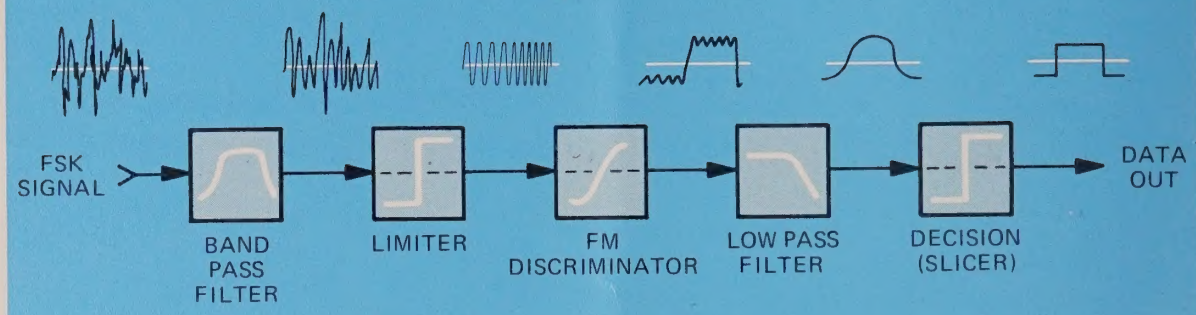


Figure 9. FM detector-type FSK demodulator.

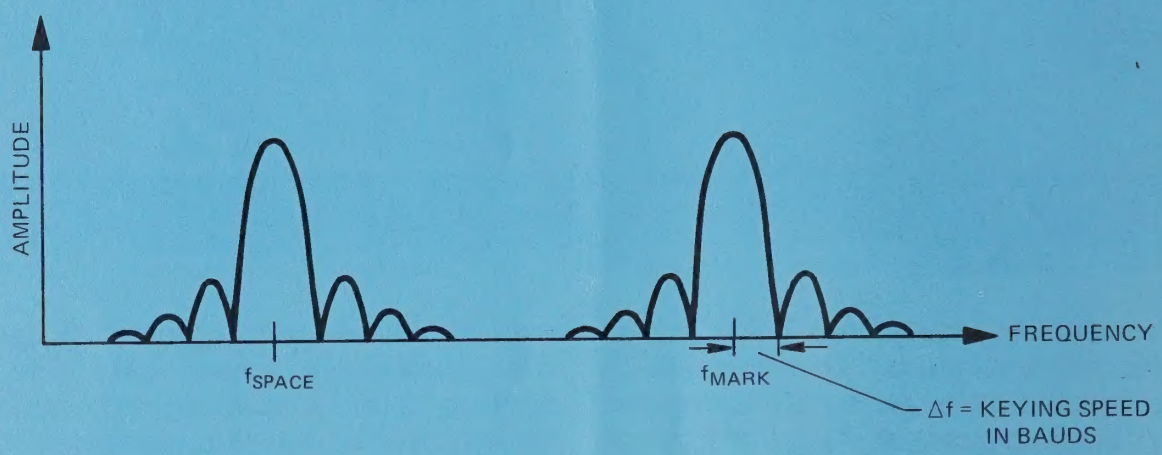


Figure 10. Simplified frequency spectrum of a typical binary FSK signal.

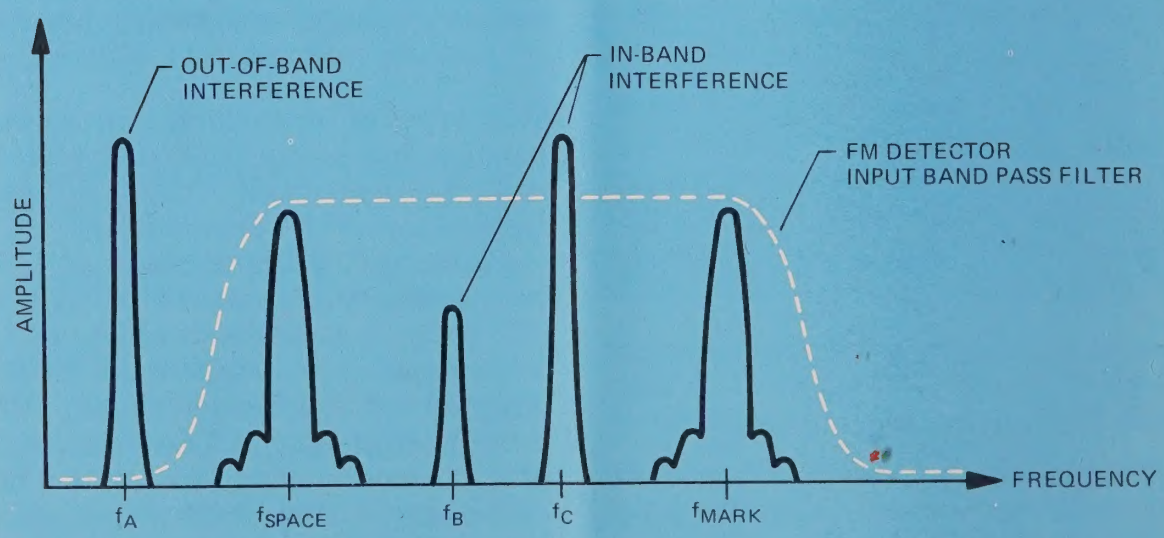


Figure 11. FSK signal spectrum with in-band and out-of-band interference.

FM-type detectors are non-optimal in the sense that they perform more poorly than signal detection theory would predict is possible. To see why this is true, it is necessary to examine the spectrum of a typical FSK signal. As shown in Figure 10, it can be seen that virtually all the energy in the mark and space tones is within a bandwidth equal to twice the baud rate, centered about the mark and space frequencies, respectively. Figure 11 shows the FSK signal spectrum with interfering signals. The interfering signal at f_A is rejected because it is out of the passband of the FM detector input filter. The interfering signal at f_B is rejected by the action of the FM limiter, which forces the strongest signal to dominate (FM "capture" effect). Unfortunately, the interfering signal at f_C is the strongest in-band signal and, as a result, completely prevents demodulation of the desired FSK signal. In the case of selective fading, as shown in Figure 12, even though the space signal is stronger than the in-band interference, the amplitude of the mark signal, reduced by multipath fading, is less than that of the in-band interference. Therefore, during mark transmissions, demodulation is severely affected. More difficult to show graphically is the effect of broadband "white" noise interference. If the envelope of the noise exceeds that of the FSK signal, demodulation is prevented.

A comparison of the FSK spectrum with the spectrum over which an FM-type FSK detector is sensitive to interference leads to the conclusion that the performance of an FM-type FSK detector is severely limited by its relatively wide input bandwidth. The inclusion of large portions of frequency spectrum that do not contain significant signal energy is clearly a non-optimal approach to FSK demodulation.

At this point it is appropriate to ask, "What is the optimum demodulation method?" Using signal-detection theory, it can be shown that a "matched-filter" detector will give the theoretically best demodulation performance.

Filter-Type FSK Demodulators

Filter-type demodulators attempt to optimally match the FSK signal parameters to the demodulator configuration to optimize demodulator error

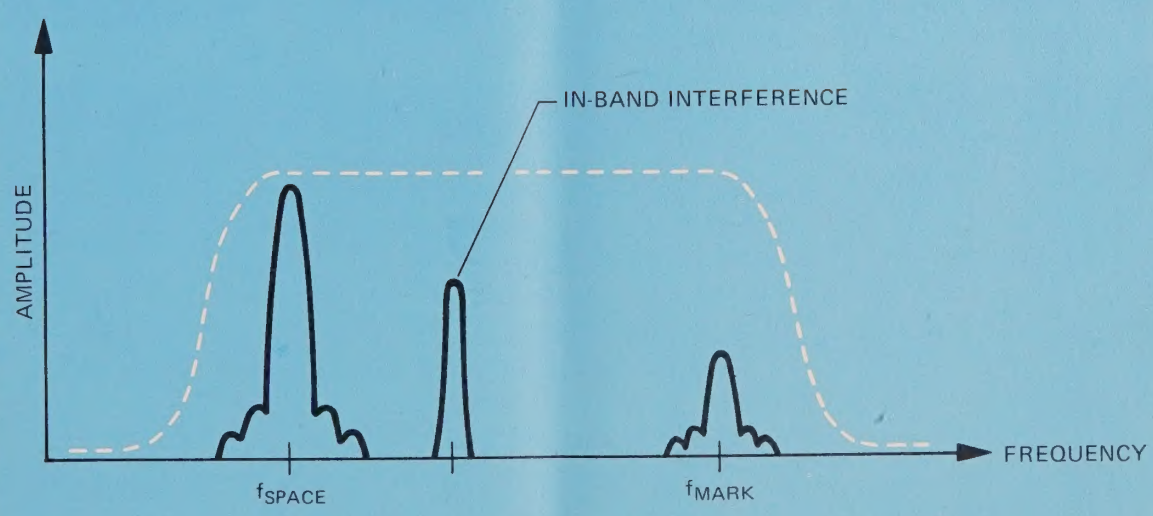


Figure 12. FSK signal spectrum with in-band interference and selective fading.

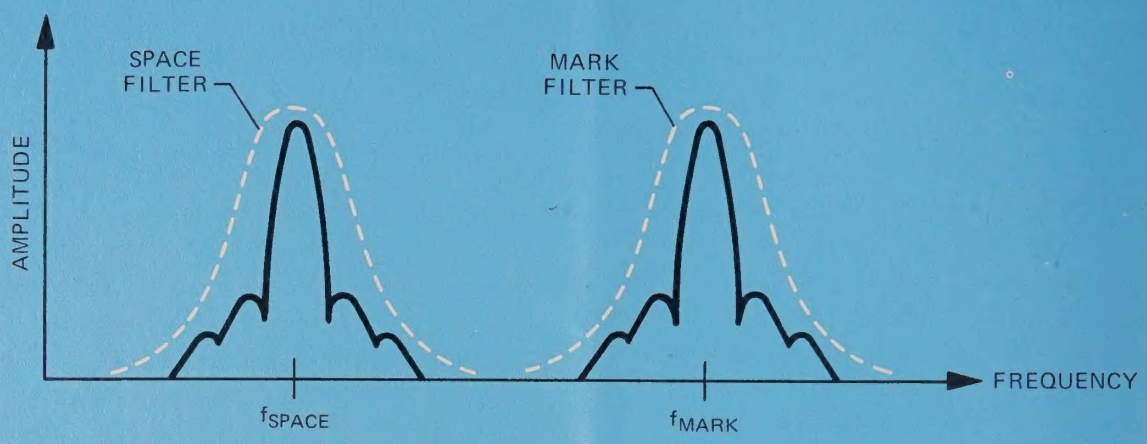


Figure 13. Simplified demodulation spectrum for filter type FSK demodulators.

performance. A simplified spectrum for filter-type demodulators is shown in Figure 13. The proper filter design depends not only on the signal parameters, but also on the nature of the signal interference. The classic "matched" filter demodulator is optimal for coherent FSK in white gaussian noise interference. Other filter-type demodulators are used for noncoherent FSK and/or nonstochastic noise environments.

A block diagram of a simple, matched-filter demodulator for coherent FSK is shown in Figure 14. In the demodulator, the output of the matched filters is compared, and if the output from the mark filter is larger than that from the space filter, a decision is made that a mark signal was transmitted. Space detection is similarly performed. A matched filter demodulator is optimum because its filters are "matched" to the transmitted signal so that their response to the desired signal is maximized with respect to their noise response. For white noise, the optimum filter has an impulse response equal to the time-reversed, input signaling element. Because noncoherent FSK is so much more common than coherent FSK, it is necessary to have a type of demodulator that does not depend on phase information.

Optimum demodulation of noncoherent FSK can be achieved by envelope detection of the signal filter outputs in a filter-type demodulator. A demodulator of this type is shown

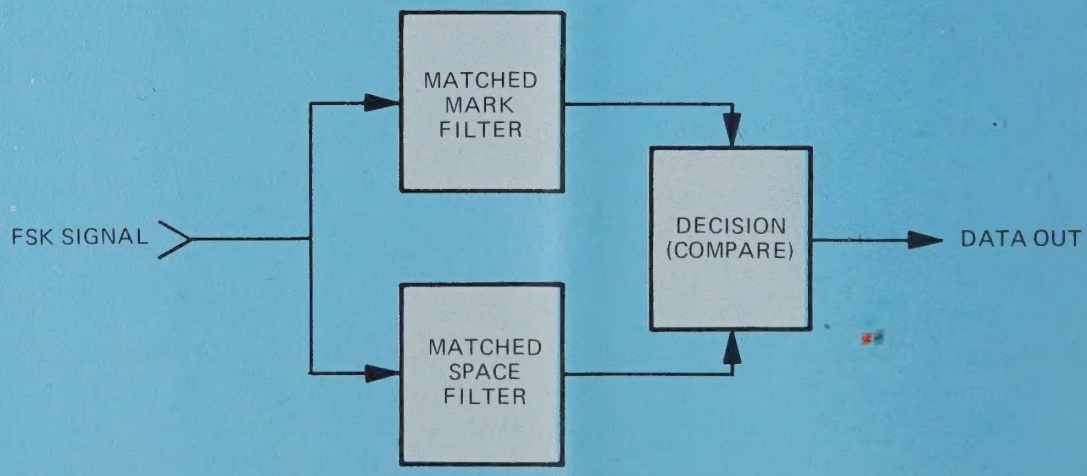


Figure 14. Matched filter FSK demodulator.

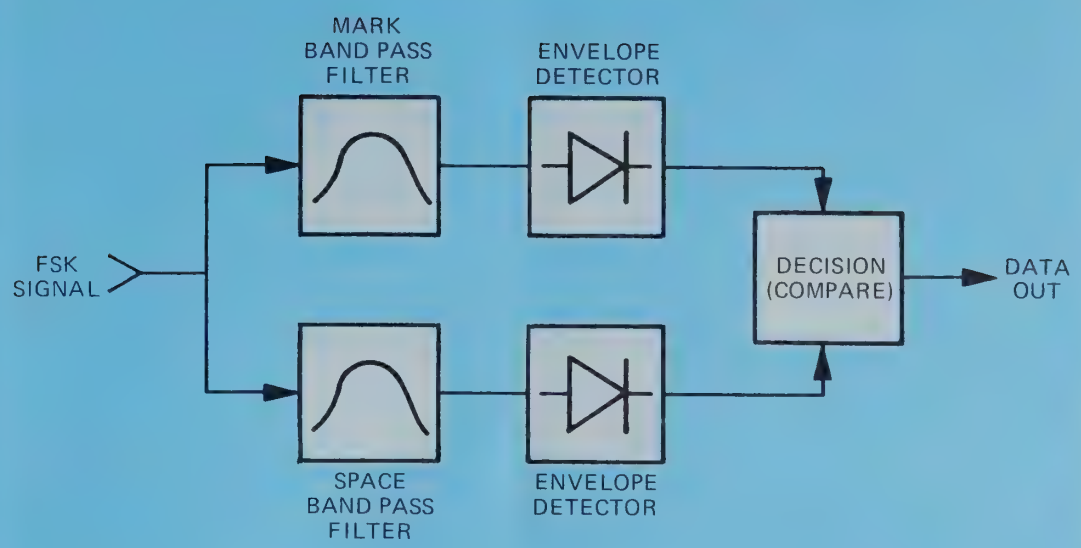


Figure 15. Non-coherent FSK demodulation with spectrally matched filters and envelope detection.

in Figure 15. The outputs of the mark and space filters are envelope-detected and then compared to determine which has greater magnitude. Note that phase information is not required. With the "right" filter shape, performance of this type of demodulator approaches the theoretical optimum for noncoherent FSK. The "right" filter shape for a white noise interference environment is one that has the same spectral shape as the transmitted signal. For the "rectangular" modulation of FSK, the right shape is a sinc function

$$\left(\frac{\sin x}{x}\right)$$

bandpass filter centered about the desired mark or space tone. The spectral shape of optimum mark and space filters would be the same as that of the mark and space spectrum of Figure 10. Unfortunately, the assumption of white noise interference is not justified in most real signal environments.

For the general case of noncoherent FSK with non-white noise interference, the problem of optimum filter design is more complex. Two common types of non-white noise interference are adjacent channel interference and CW interference. Because of the unpredictable nature of this kind of interference, it is desirable to create a filter type which performs well with both white and non-white interference. To minimize the effect of non-white interference, it is desirable to use a bandpass filter with relatively steep attenuation skirts and without the side lobes that are characteristic of the sinc-function filter. It is also desirable that the filter perform well in white noise.

For each filter shape, there is an optimum bandwidth. In general, if the filter bandwidth is too wide, excess noise energy will be included. If the filter bandwidth is too narrow, consecutive signal elements will interfere with each other. This is called intersymbol interference. In narrow filters, this is caused by "ringing" or by the filters inability to "dump" the energy of the previous element before the next element is received.

To specify filter characteristics, it is convenient to talk in terms of the filter's 3-dB bandwidth. The optimum 3-dB bandwidth varies directly with the signal keying speed and inversely with element length. If we

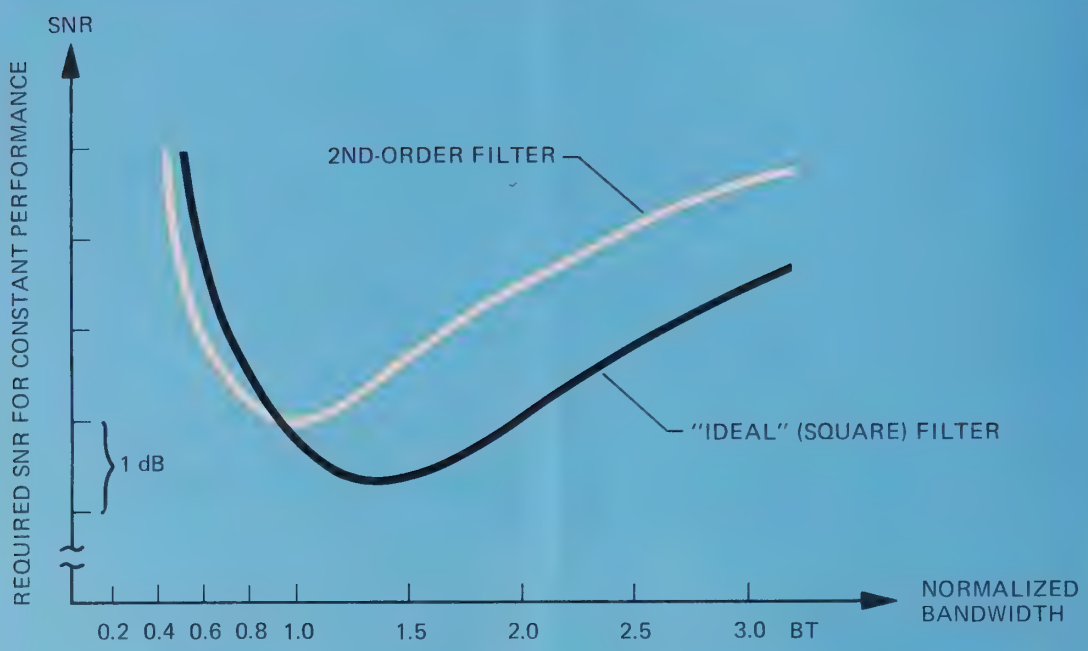


Figure 16. Constant error performance curves for two FSK filter types.

consider filters with a bandwidth normalized by multiplying the 3-dB bandwidth (B) by the element length (T), we can plot a single performance curve for each filter shape, independent of system keying speed. Figure 16 plots normalized filter bandwidth versus the signal-to-noise ratio (SNR) for constant error performance in white noise. Optimum normalized bandwidth for each filter is at the SNR minimum. To the left of the SNR minimum, intersymbol interference dominates. To the right, excess white noise energy is the dominant interferer.

By selecting a filter type which has both good white-noise performance and steep attenuation skirts, excellent noncoherent FSK demodulation is possible in either white or nonwhite noise interference. The filters used in the WJ-9470/DU demodulator module have white noise error performance that is within a small fraction of 1 dB, relative to theoretically optimum white-noise type filters. The WJ-9470/DU filters also have steep attenuation skirts which maximize performance in a nonwhite noise environment. The filter bandwidths and center frequencies must be independently variable over a wide range to optimally match the signal parameters of keying speed and shift. In the WJ-9470/DU, this flexibility is accomplished by using variable bandpass filter synthesis. This allows crystal-controlled frequency selection to 1-Hz accuracy and baud-rate matching with nearly 200 different bandwidths.

Decision Threshold Selection

The decision element of Figure 15 can be realized by several different circuit configurations. The simplest decision circuit is a voltage comparator which decides that a mark signal was received if the output from the mark detector is greater than the "noise" output from the space detector. With equal amplitude transmitted signals and no selective fading, this is the theoretically optimum decision circuit. The error performance of this type of decision for binary noncoherent FSK in white noise is shown in Figure 17. If the FSK signal is subject to selective fading (Rayleigh amplitude statistics),

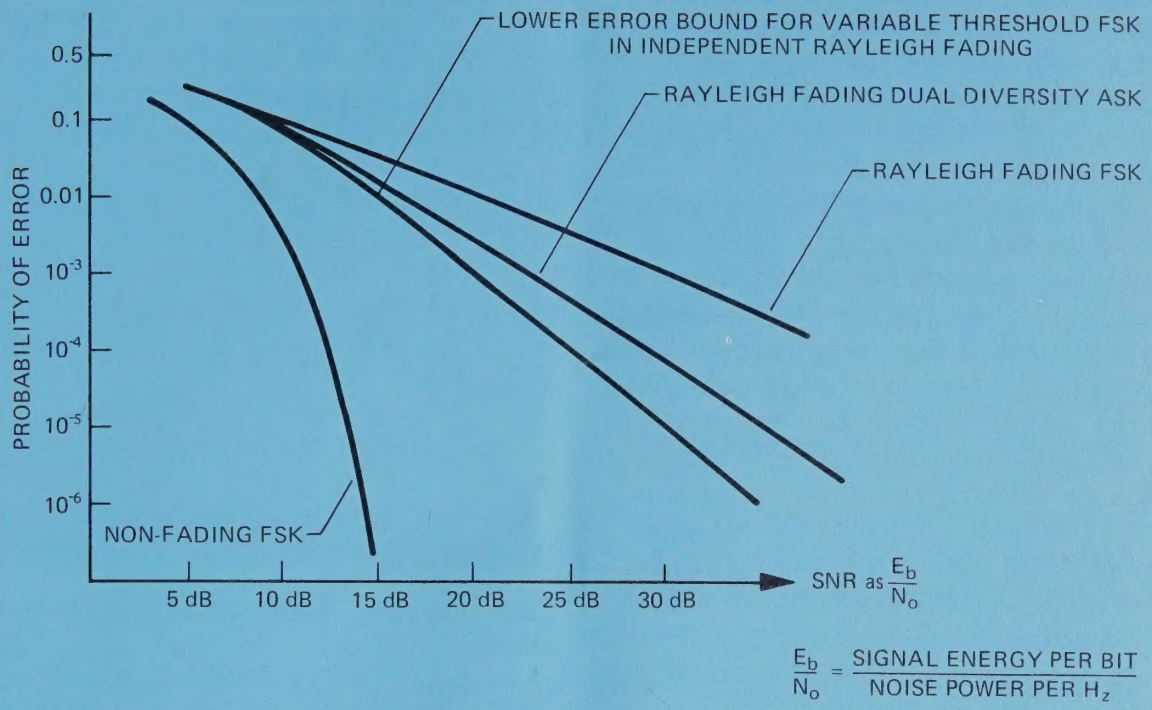


Figure 17. Error performance for nonfading and Rayleigh fading FSK.

the performance of the demodulator is severely degraded.

If the mark and space tones are separated in frequency so that they fade independently, it is possible to differentially sum the outputs of the mark and space detectors to diversity-combine the signals. Figure 18(a) shows the combined output for alternating mark and space transmissions. The envelopes of the mark and space detector voltages vary with the fading mark and space signal

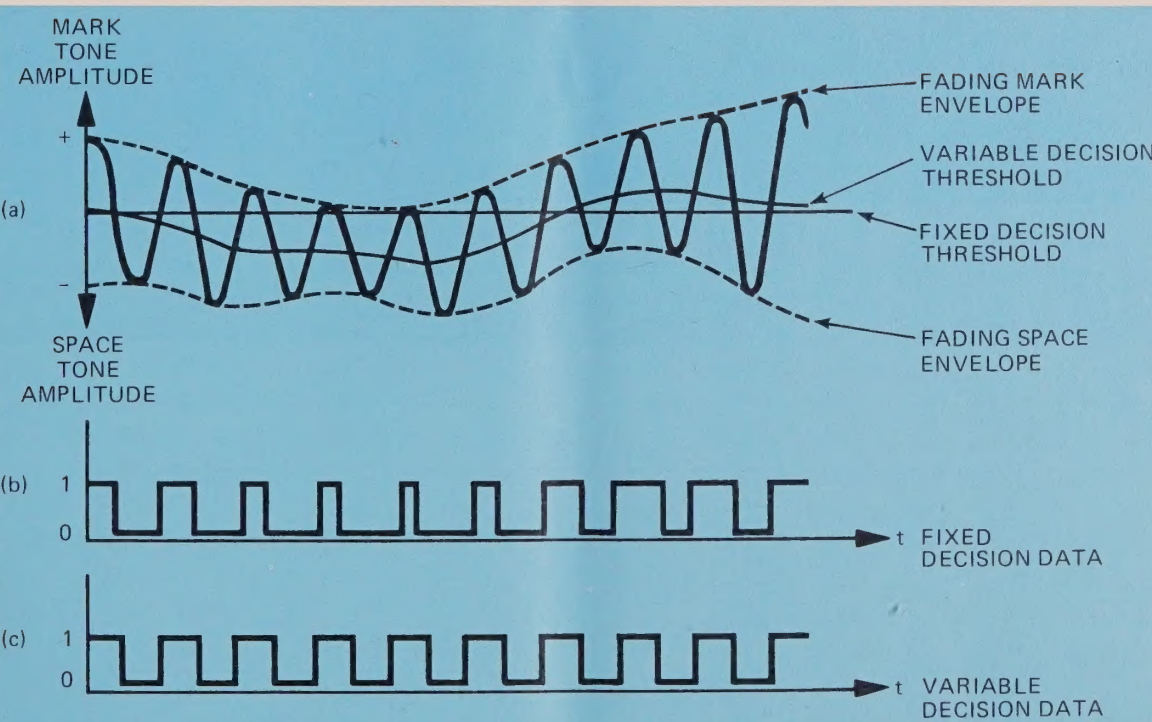


Figure 18. Independent fading FSK with fixed and variable decision thresholds. The differential sum (a) of the mark and space detectors produces distorted data (b) with a fixed decision threshold and undistorted data (c) with a variable decision threshold.

amplitudes. In the summing configuration, the decision circuit compares the differential sum with a voltage reference, which determines the decision "threshold." When the sum is greater than the threshold, a mark decision is made and when the sum is less than the threshold, a space decision is made. When the signal has equal mark and space amplitudes, the optimum threshold is a fixed zero-voltage reference. However, during selective fading conditions, it is necessary to dynamically vary the decision threshold to achieve optimum demodulation. The effect of selective fading on signal data with fixed and variable thresholds is demonstrated in Figure 18(b) and (c).

Performance of a variable-threshold detector can be compared to diversity demodulation of two independently fading, amplitude-shift-keyed (ASK) signals. In fact, because of the differential nature of the mark and space signals, error performance can be better than that predicted for diversity ASK. The error performance of diversity ASK and a lower error bound limit of performance for variable threshold FSK are shown in Figure 17. For best performance, the parameters of the variable threshold detection circuitry must be optimized with respect to the signal characteristics. The WJ-9470/DU uses a variable threshold detector which is optimized to match both the signal keying rate in bauds and the keying duty cycle dynamics.

Conclusion

FSK signals take many different forms depending on their intended application. With the increasing sophistication of electronics and signal detection theory, it is clear that new FSK demodulators, like the WJ-9470 series, are required to optimally demodulate the many different signal formats. It is the task of today's FSK demodulator to take the potential of FSK and reduce theory to practice.

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